

Massive black hole seeds born via direct gas collapse in galaxy mergers: their properties, statistics and environment

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ABSTRACT

We study the statistics and cosmic evolution of massive black hole seeds formed during major mergers of gas-rich late-type galaxies. Generalizing the results of the hydro-simulations from Mayer et al. (2010), we envision a scenario in which a supermassive star can form at the center of galaxies that just experienced a major merger owing to a multi-scale powerful gas inflow, provided that such galaxies live in haloes with masses above $10^{11} M_{\odot}$, are gas-rich and disc-dominated, and do not already host a massive black hole. We assume that the ultimate collapse of the supermassive star leads to the rapid formation of a black hole of $10^5 M_{\odot}$ following a quasi-star stage. Using a model for galaxy formation applied to the outputs of the Millennium Simulation, we show that the conditions required for this massive black hole formation route to take place in the concordance Λ CDM model are actually common at high redshift, and can be realized even at low redshift. Most major mergers above $z \sim 4$ in haloes with mass $> 10^{11} M_{\odot}$ can lead to the formation of a massive seed and, at $z \sim 2$, the fraction of favourable mergers decreases to about half. Interestingly, we find that even in the local universe a fraction ($\sim 20\%$) of major mergers in massive haloes still satisfy the conditions for our massive black hole formation route. Those late events take place in galaxies with a markedly low clustering amplitude, that have lived in isolation for most of their life, and that are experiencing a major merger for the first time. We predict that massive black hole seeds from galaxy mergers can dominate the massive end of the mass function at high ($z > 4$) and intermediate ($z \sim 2$) redshifts relative to lighter seeds formed at higher redshift, for example, by the collapse of Pop III stars. Finally, a fraction of these massive seeds could lie, soon after formation, above the $M_{\text{BH}} - M_{\text{Bulge}}$ relation.

Key words: galaxies: active - galaxies: formation - quasars: general - cosmology: observations - cosmology: theory

1 INTRODUCTION

Accreting black holes of masses $> 10^8 M_{\odot}$ are the only known astrophysical objects able to produce the enormous amount of energy released by active galactic nuclei (AGN, Lynden-Bell 1969), and the brightest of these objects, *quasars*, are seen at redshifts as high as ~ 7 (Mortlock 2011). The existence of supermassive black holes (black holes with mass $> 10^6 M_{\odot}$) at the center of nearby non-active galaxies has been also confirmed in the last few decades thanks to the observation of the gravitational influence of these objects on the surrounding gas and stars (e.g., Kormendy 2004).

While the existence of black holes in the cores of most massive galaxies is now well established, their origin is still largely unknown. Several channels of black hole formation have been envisioned and explored, but when and where the progenitors (“seeds”) of these massive black holes formed, is still a topic of intense theoretical investigation. According to the “PopIII” scenario, black holes are the descendant of Population III stars, the first generation

of stars formed from pristine gas in dark matter haloes of $\sim 10^6 M_{\odot}$ (e.g., Bond et al. 1984; Madau & Rees 2001; Haiman & Hui 2001); these remnant black holes would have masses of few tens or few hundreds of solar masses, although recent numerical simulations have shown that the protostellar disk of PopIII stars could fragment, lowering the initial mass function of the stars and, consequently, of their remnant black holes (Clark et al. 2011; Greif 2011). To grow in a short time to one billion solar masses (the mass estimated for the black holes powering the quasars seen at $z \sim 6$), the Pop III remnants would have to have formed at $z \gtrsim 20$ and accrete gas almost continuously at a rate close to the Eddington limit (e.g. Volonteri & Rees 2006; Tanaka & Haiman 2009; Tanaka et al. 2012). Black holes could also come from the runaway collapse of nuclear star clusters, but even in this case the black hole starting mass would not be higher than $\sim 10^3 M_{\odot}$ (e.g., Rasio et al. 2004; Portegies Zwart & McMillan 2002; Devecchi & Volonteri 2009).

To relax the tight constraints on growth rates and formation

times required to build up the very massive black holes powering high- z quasars, the “direct collapse” scenario has become more and more attractive, as the starting black hole mass could be few orders of magnitude higher ($10^4 - 10^6 M_\odot$). Such massive black hole seeds originate from dense clouds of gas (Rees 1984) at the center of galaxies (or protogalaxies) and likely collapse into a “supermassive” star; the supermassive star would then either entirely collapse into a black hole if gravitationally unstable (e.g., Hoyle & Fowler 1963; Baumgarte & Shapiro 1999; Shibata & Shapiro 2002; Montero et al. 2012), or form a massive black hole via a “quasi-star” (Begelman et al. 2008; Begelman 2010). In the direct collapse scenario, the most difficult step is to get a massive and dense enough central gas cloud, as the gas has to lose its initial angular momentum and reach the galactic center before cooling and fragmentation are able to trigger star formation. Most works in the literature have focused on the formation of black holes from direct collapse in metal-free protogalaxies (e.g., Lodato & Natarajan 2006; Wise et al. 2008; Regan & Haehnelt 2009; Johnson et al. 2011), as even small traces of metals shorten the gas cooling time significantly (Omukai et al. 2008). Even in a metal-free environment, though, molecular hydrogen cooling has also to be prevented, which may be possible thanks to fluctuations in the Lyman-Werner background (Dijkstra et al. 2008; Agarwal et al. 2012). One could relax the assumption of a metal-free environment if the gas inflow rate to the center is higher than star formation rate, that is, if enough gas can be brought to the center before the bulk of star formation takes place (Shlosman et al. 1989; Begelman & Shlosman 2009).

Mayer et al. (2010, hereafter, M10) have recently shown that very efficient central inflow rates are possible in gas-rich galaxy major mergers. Using a set of numerical simulations with extremely high spatial resolution (0.1pc), M10 found that mergers can produce a gravito-turbulent disk in the nuclear region of the remnant galaxy. The disc is stable against fragmentation, but features a strong spiral pattern which supports efficient inflow of gas towards the galactic center. This strong inflow produces a central rotating cloud of $\sim 10^8 M_\odot$ and of the size of few parsecs, which soon becomes Jeans unstable and collapses to sub-parsec scales. The inflow rates from the nuclear disc are so strong (up to few thousands of solar-masses per year), that this happens in only about 10^5 yr. The resolution of the simulation does not allow to investigate further the fate of the nuclear cloud, but the cloud is seen to be Jeans unstable down to the smallest resolved scales. This collapsing cloud is thus a likely precursor of a supermassive star. Soon after formation, the core of rotating supermassive stars is likely to collapse into a black hole of $\sim 100 M_\odot$, as the timescale of nuclear burning is very short (~ 1 Myr). In the “quasi-star” picture (Begelman et al. 2008; Begelman 2010), as the central black hole starts accreting, the surrounding gas is inflated into a pressure-supported envelope. While the envelope loses mass through winds, the black hole keeps accreting at super-Eddington rates, as the Eddington limit is imposed on the much larger mass of the envelope, and not on the mass of the black hole itself. Dotan et al. (2011) estimated that black holes in this configuration can quickly grow to $10^4 - 10^5 M_\odot$, provided that their surrounding envelopes are above $\sim 10^7 M_\odot$, as they would be massive enough for their evaporation timescale to be longer than the accretion timescale of the black hole.

Inspired by the numerical results of M10 and the idea of massive black hole seeds forming from the collapse of nuclear clouds via a supermassive star, in the present work we construct an analytical model for the formation of massive seeds in galaxy mergers to be incorporated in a galaxy formation model applied to the out-

puts of the Millennium Simulation. Our aim is to study whether the conditions for the formation of a massive seed can actually be met in our Universe, what would be the contribution of black holes from massive seeds to the total black hole population and whether the descendants of massive seeds could be observationally recognized. Volonteri & Begelman (2010) made a first attempt to study the cosmological evolution of massive seeds from quasi-stars, linking their formation to the mergers of gas-rich dark matter haloes and the spin of the haloes, using observational properties of the black hole population to bracket the values of their model parameters. In the present work we instead directly use the results of the M10 hydro-simulations to construct a model for the formation of massive seeds with essentially no free parameters, whose predictions can be directly compared with data.

In section §2 we describe in further details the simulations of M10, and how we generalize their results to create the analytic model used in the galaxy formation simulations. Section §3 contains the results of the paper, which we summarize and discuss in section §4.

2 MODEL

In this section we first describe the general properties of the galaxy formation formalism upon which we construct the model for the formation and evolution of black hole seeds (§2.1). We then discuss the details of our modeling, the origin of the population of “light” black hole seeds (§2.2) and the details of the hydro-simulations of M10 that inspired our model for the formation of the “massive” seed population as described at the end of §2.3.

2.1 The model of galaxy formation

In the last couple of decades, semi-analytical models of galaxy formation have been extensively exploited to study the basic physical processes that drive galaxy evolution by comparing the global properties of simulated galaxies with observational data (e.g., Kauffmann et al. 1993; Somerville & Primack 1999; Bower et al. 2006). Indeed, semi-analytical models offer a simple approach to study large samples of galaxies, whose formation and evolution is described by a set of coupled differential equations that combine baryonic physics with the properties of dark matter halo assembly histories constructed from the extended Press & Schechter formalism or from N-body cosmological simulations.

The model used in this work uses the dark matter merger trees extracted from the outputs of the Millennium Simulation (Springel et al. 2005), an N-body simulation which follows the evolution of cosmic structures in a $500^3 h^{-3} \text{Mpc}^3$ volume using $2160^3 \simeq 10^{10}$ dark matter particles of mass $\sim 8.6 \times 10^8 h^{-1} M_\odot$. The initial conditions of the Millennium Simulation are based on the cosmological parameters of the WMAP1 & 2dFGRS ‘concordance’ Λ CDM framework¹, with $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\sigma_8 = 0.9$, Hubble parameter $h = H_0/100 \text{ kms}^{-1} \text{Mpc}^{-1} = 0.73$ and primordial spectral index $n = 1$ (Spergel et al. 2003). DM haloes and the embedded subhaloes are identified from the output of the simulation with a friends-of-friends (FOF) group-finder and an extended version of the SUBFIND algorithm (Springel et al. 2001), respectively. Dark matter haloes are considered to be resolved when their

¹ Guo et al. (2012) showed that there are little differences in the galaxy properties when a WMAP7 cosmology is assumed

mass is above $\sim 10^{10} h^{-1} M_{\odot}$, equivalent to 20 simulation particles. The galaxy formation model follows the merger history of dark matter haloes and, when a new halo rises above the resolution limit, it gets populated by baryons in the form of hot gas (according to the cosmic baryon fraction), which will start cooling and forming stars according to the analytical prescriptions adopted. We refer the reader to Croton et al. (2006) and De Lucia & Blaizot (2007) for all the details on the prescriptions for gas cooling, star formation, supernovae feedback and the other physical processes that shape galaxies and their morphology across cosmic times, and for a description of the model success in reproducing many properties of the observed galaxy population. Here, we modify only the assumptions for the formation and evolution of supermassive black holes.

We consider two different black hole seed formation scenarios. The first one assumes that seeds originate from relatively **light seeds**, either from massive Population III stars or from the runaway collapse of a nuclear star cluster. This scenario has been already adopted in a number of published works on the co-evolution of galaxies and black holes and on the clustering of QSOs that are based on the same model of galaxy formation used in this paper (Marulli et al. 2008; Bonoli et al. 2009). The second channel of black hole seed formation that we introduce in this work is based on the results of M10 presented above, and aims at describing the formation of **massive seeds** in major mergers of gas-rich galaxies.

2.2 Light black hole seeds

We assume that every newly-resolved galaxy in the simulation contains a black hole descendant of black hole seeds from PopIII stars or the runaway collapse of nuclear star clusters, which likely formed in protogalaxies at $z > 10$ (e.g., Madau & Rees 2001; Devecchi et al. 2010). Given the limited mass resolution of the Millennium Simulation, we can not directly track the formation and early evolution of these objects in our galaxy formation model, so we have to make some assumptions on the mass of these “light” seeds descendants. Marulli et al. (2008) and Bonoli et al. (2009) had assumed a fixed mass for these black holes as the global properties of black holes and quasars at moderate and low redshift ($\sim z < 5$), as simulated by our galaxy formation model, are essentially insensitive to the mass assigned to black holes in newly-formed galaxies, since any subsequent exponential growth washes out traces of the starting mass. However, as we will discuss in detail below, our new model for the formation of massive seeds in galaxy merger requires an accurate census of the mass of black holes, descendant of light seeds, at any time. For this work, we then decided to assume that the mass of the descendant of *light seeds* in newly formed galaxies depends on the mass of the newly-resolved halo they reside in and on the redshift at which the halo is resolved. We use the results of a higher resolution simulation, the Millennium-II², to construct a “library” of typical black hole masses, as a function of halo mass and redshift. Thanks to the much higher mass resolution of the Millennium-II, mergers of galaxies residing in subhaloes down to few times $10^8 h^{-1} M_{\odot}$ are properly followed. Guo (2011) have generated a galaxy catalogue for this simulation, with black holes forming and growing during galaxy

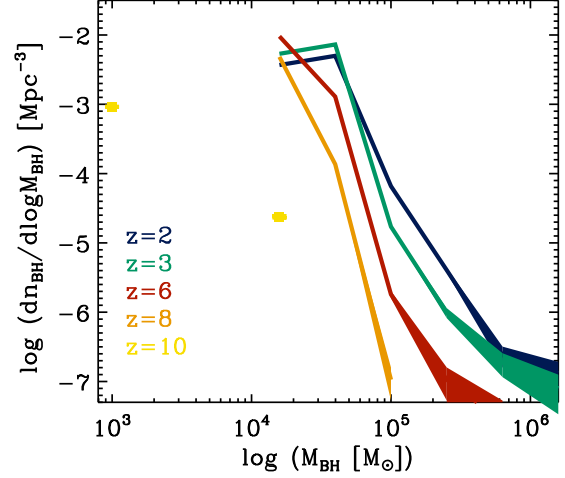


Figure 1. Mass function of the initial black holes, descending from light seeds, that populate newly formed galaxies. Each curve corresponds to a different redshift of formation of the host galaxy, as indicated by the legend. Note that at $z = 10$ the initial black holes can only take the values $10^3 M_{\odot}$ and $10^4 M_{\odot}$.

mergers as in Croton et al. (2006), and we use this catalogue³ to generate our “library”. To compensate for still limited resolution of the Millennium-II, we impose a minimum mass of $10^3 M_{\odot}$ for these light black hole seed descendants (but we note that the results presented in this paper are insensitive to the exact value of the minimum black hole mass imposed). In Figure 1 we show, at various redshifts, the mass function of the black holes populating newly resolved galaxies, which are assumed to be the descendants of light seeds. At $z = 10$ the typical assigned masses are 10^3 or $10^4 M_{\odot}$. As redshift decreases, the mass assigned to new black holes is higher and, for galaxies resolved at $z < 3$, it can even be higher than $10^6 M_{\odot}$.

These black holes will keep growing mainly during galaxy mergers. When a merger takes place, we assume that the black holes hosted by the two galaxies coalesce instantaneously (so that each galaxy hosts only one black hole at a time), and the resulting black hole starts accreting a fraction ΔM_{BH} of the surrounding cold gas m_{cold} which depends on the mass ratio of the merging galaxies ($m_{\text{sat}}/m_{\text{central}}$) and the redshift of the merger (as in Croton 2006). Specifically, the amount of gas accreted by a black hole during a galaxy merger is given by:

$$\Delta M_{\text{BH,merger}} = \frac{f'_{\text{BH}} m_{\text{cold}}}{1 + (280 \text{ km s}^{-1} / V_{\text{vir}})^2} (1 + z_{\text{merg}}), \quad (1)$$

where m_{cold} is the total mass of cold gas in the final galaxy and $f'_{\text{BH}} = f_{\text{BH}} (m_{\text{sat}}/m_{\text{central}})$ and $f_{\text{BH}} \approx 0.02$ is a normalization parameter chosen to match the observed local $M_{\text{BH}} - M_{\text{Bulge}}$. This prescription has been shown to be successful in reproducing not only the $M_{\text{BH}} - M_{\text{Bulge}}$ relations, but also the black hole mass function at $z = 0$ and other observed properties of black holes, quasars and their environment (Marulli et al. 2008; Bonoli et al. 2009), and the choice of populating newly-formed galaxies with the typical

² The MillenniumII is an N-body simulation with the same particle number and cosmology of the Millennium, but 125 times better mass resolution since run in a volume of $100^3 h^{-3} \text{Mpc}^3$.

³ from the online database <http://www.mpa-garching.mpg.de/Millennium/> (Lemson & Virgo Consortium 2006)

black holes found in the Millennium-II does not modify these results.

2.3 Massive Black Hole Seeds

The model we construct for the formation of massive black hole seeds from galaxy mergers is based on the assumptions and results of the hydro-simulations of M10. We thus first describe their results and then how we generalize them to build a model to be used in the galaxy formation framework described above.

2.3.1 The evolution of the nuclear region of merger remnants according to hydro-simulations

M10 have used a set of numerical simulations to study the evolution of the nuclear region of high-redshift major-merger remnants. The initial conditions of such mergers will be used in the analytical model that we develop in this paper. The model galaxies adopted in M10 are disk dominated galaxies (the bulge-to-disk mass ratio is typical of present-day late type spirals, i.e. $B/D = 0.2$), with a gas/stars fraction in the disk of 20% just before the merger occurs (some gas can be consumed by star formation during the tidal interaction preceding the merger, an effect that will depend on the details of the orbital parameters and internal structure of the merging galaxies). The choice of the gas fraction is conservative since high- z disks can be significantly more gas-rich (Genzel 2006). Only equal mass mergers of galaxies were considered, with a dark host halo mass range between 5×10^{10} to $10^{12} M_{\odot}$. At lower mass scales outflows driven by supernovae feedback should dominate the gas dynamics and thermodynamics, preventing central accumulation of gas (Governato et al. 2010). Mergers with mass ratio below 1 : 3 have been shown to be much less efficient at concentrating gas to the inner few tens of parsecs (Callegari et al. 2009; Guedes et al. 2011), and were therefore not considered in M10 nor they will be in the model formulated in this paper.

Thanks to the unprecedented spatial resolution of their experiments (the softening length of the gas in the nucleus is 0.1 pc), MA10 find that major mergers of disk and gas-rich galaxies in haloes above $10^{11} M_{\odot}$ are responsible for a very strong inflow of gas down to scales of a few parsecs, peaking at $> 10^4 M_{\odot}/\text{yr}$. A key point in this result is that the resulting inflow rates are a few orders of magnitude higher than those found in simulations of nearly isolated unstable self-gravitating protogalactic disks ($\sim 10^3 - 10^4 M_{\odot}/\text{yr}$ vs. a few tens of solar masses/year, see e.g., Regan & Haehnel 2009). The reason is that in mergers gas can be shocked and torqued much more effectively, losing most of its angular momentum over a short timescale.

A much higher predicted inflow rate is also a difference with respect to semi-analytical models of seed black hole formation via direct collapse (e.g. Volonteri & Begelman 2010), which consider the conditions at the virial radius of the host galaxy halo. Indeed, in M10 gas flows inward owing to continuous loss of angular momentum by torques and shocks over a wide range of spatial scales (at small scales the torques are provided by spiral arms in the unstable nuclear disk arising at the center of the merger remnant). The net inflow rate at the center thus depends on the integrated effect of all the torques at different scales rather than on the conditions at the global galactic or halo scales. The resulting characteristic velocity of the gas is much higher than the free fall velocity at the halo virial radius, while the gas mass reservoir is still within a factor of a few of the total amount of gas available in the galaxy even at relatively

small scales (i.e. the nuclear disk acquires most of the cold gas mass in the galaxy due to angular momentum loss at large scales). Ultimately, this translates into a much higher mass inflow rate that well exceeds the expectation using free fall velocity at the scale of the halo. The latter is given by:

$$dM/dt = m_d V_c^3 / G, \quad (2)$$

where G is the gravitational constant, V_c is the virial circular velocity of the dark matter halo hosting the galaxy and m_d indicates the fraction of mass which is able to collapse in free fall. For $V_c \sim 150 - 200 \text{ km/s}$, which were the typical values of the virial velocities of the haloes simulated by M10, one would obtain $dM/dt \sim \text{few tens of } M_{\odot}/\text{yr}$ (assuming $m_d = 0.05 - 0.1$ as in Lodato & Natarajan (2006)), which is several orders of magnitude lower than what is found in the sub-pc scale merger simulations. Likewise, while Volonteri & Begelman (2010) (see also Lodato & Natarajan 2006; Volonteri et al. 2008) use a threshold in spin parameter of the halo as a further criterion to decide which haloes would undergo seed formation via direct collapse, we avoid that based on the fact that the angular momentum of the gas likely does not trace that of dark matter at any scale (e.g., Dubois 2012), and especially at small scales the dynamics of the nuclear disk dominates the evolution of the angular momentum.

Shortly after the merger, the central region of the galaxy remnant in M10 is characterized essentially by two components:

- a rotating nuclear disk, of the size of about ~ 80 pc and mass of $\sim 10^9 M_{\odot}$. It is in this disk where a very large fraction of the gas initially in the galactic disk has accumulated;
- a pressure-supported rotating cloud of the size of few parsecs, and of mass of $\sim 10^8 M_{\odot}$. This cloud forms from the rapid inflow of gas from the nuclear disk less than a million years after the merger. Due to this strong inflow from the surrounding disk, the cloud becomes Jeans unstable, and eventually collapses to sub-parsec scales.

Once the cloud shrinks to the resolution limit (0.1 pc) the simulation cannot follow the collapse further, hence whether it forms a supermassive star first or collapses all the way into a seed black hole is uncertain at this stage. Both processes, however, would lead to the formation of a massive seed on timescales short enough ($< 10^7$ yr even in the case of the slower route via a supermassive star stage) that, for the purpose of this work we will consider instantaneous. The mass of the seed in the runaway gravitational collapse case could be much larger, comparable with the mass of the cloud, but we will consider the supermassive star route in order to be conservative ($M \sim 10^5 M_{\odot}$, see Begelman (2010) and, for the cases of the large inflow rates considered here, Dotan et al. (2011)). The circumnuclear disk + supermassive cloud configuration is the underlying structure that we will consider to construct our phenomenological recipe of massive seed formation and growth.

2.3.2 Massive black hole seeds in the galaxy formation model

In our new model, we assume that massive black hole seeds form during the major mergers of massive gas-rich late-type galaxies that satisfy specific constraints. Mimicking the initial conditions used in the simulations of M10, the exact conditions for inserting a massive seed are the following:

- (i) **A major merger.** We impose a minimum mass ratio $M_{\text{gal},1}/M_{\text{gal},2}$ of 0.3, where with M_{gal} we refer to the stellar+cold-gas component of the galaxy. As discussed above, this is motivated

by simulations results (Callegari et al. 2009; Guedes et al. 2011) who showed that mergers of galaxies with smaller mass ratios are not violent enough to trigger strong gas inflows towards the galaxy center;

(ii) **A minimum mass of the dark matter halo of the merger remnant M_{halo} of $10^{11} M_{\odot}$.** M_{halo} corresponds to the subhalo mass for satellite galaxies and the virial mass for centrals. This threshold in halo mass comes from the results of the M10 simulations, which show, with varying mass of the merging galaxies, that the central collapse does not occur below such mass scale as a result of increased stability of the nuclear disk. Future analysis of an extended sample of numerical simulations will have to clarify if it is indeed the mass or rather the central density of galaxies, as probed by the maximum circular velocity V_{max} , the fundamental variable governing the mass inflow.

(iii) **A bulge to total ratio B/T of both merging galaxies of at most 0.2.** The results of M10 clearly show the importance of a disk to sustain the spiral patterns able to feed the nuclear region of the merger remnant. Galaxies with such low B/T ratio have both very large gas fractions, so they potentially have enough fuel to feed the nuclear region of the merger remnant, and the structure for a proper dynamical response to generate the required multi-scale gas inflow as a result of tidal interactions (a dominant bulge tends to stabilize a galactic disk even in the presence of strong tidal perturbations, weakening the gas inflow).

(iv) **The lack of a black hole of mass larger than $10^6 M_{\odot}$.** As pointed out by M10, any pre-existing massive black hole fed by the inflowing gas would stabilize the nuclear disk via radiative feedback. We set $10^6 M_{\odot}$ as threshold, as the feedback from smaller black holes would likely be too weak to halt the gas inflow and only massive black holes might be able to actually reach the center remnant, thanks to dynamical friction, in timescales shorter than the timescale of gas inflow and formation of the central cloud (Mayer et al. 2007; Chapon et al. 2011).

If the above conditions are met, we assume that the merger is able to give rise to the high gas inflow rates that lead to the post-merger configuration found by M10: a nuclear cloud of $10^8 M_{\odot}$ surrounded and fed by a circumnuclear disk. We assume that the central part of the cloud quickly collapses into a supermassive star which, in a short timescale, gives rise to a black hole of $\sim 10^5 M_{\odot}$ via a “quasi-star”. As the timescales for these processes are very short compared to the time resolution of the cosmological simulation, we assume that a massive seed of $10^5 M_{\odot}$ is formed as soon as the conditions on the merger described above are met.

After being formed, the seed can start accreting the gas still flowing from the circumnuclear disk to the surrounding residual cloud. We assume the circumnuclear disk to be $2/3$ of the total mass in cold gas, which is approximately the value found by M10. Such high fractions of gas in the central region of major merger remnants have also been seen in previous simulations (e.g., Barnes & Hernquist 1996). Further assuming that stars in the disc form with a 30% efficiency (which can be seen as an upper limit on the star formation efficiencies in molecular clouds at small scales, i.e. well below 100 pc, e.g., Evans et al. (2009)), about $1/3$ of the gas in the nuclear disk can feed the remnant nuclear cloud and then be available for the black hole.

With these numbers in mind, we assume that the remnant of the nuclear cloud and the gas still flowing from the nuclear disk form a “reservoir” of gas of $M_r = 2/9 M_{\text{gas}}$ (with M_{gas} being the total cold-gas mass in the galaxy), from which the newly-formed massive black hole seed can accrete. The black hole now grows at

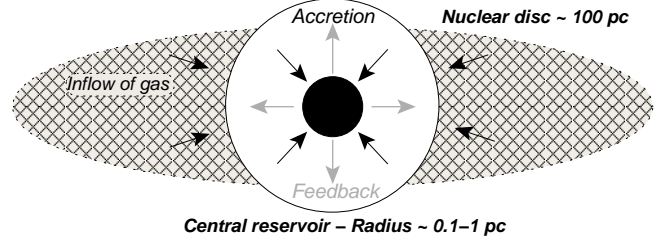


Figure 2. Sketch of the structure surrounding the massive black hole seed (of $\sim 10^5 M_{\odot}$) formed from the supermassive star after the quasi-star phase. The reservoir of gas from which the black hole grows includes the remnants of the central massive cloud from which the initial supermassive star formed and the gas still flowing from the nuclear disk. The growth of the seed stops once its feedback energy balances the binding energy of the central reservoir.

much lower rates than the super-Eddington rates that made its fast formation possible during the quasi-star phase, and it keeps growing until its feedback energy is able to unbind the reservoir (see the sketch in Figure 2).

Equating the total energy emitted by the black hole during the accretion phase and the binding energy of the gas reservoir, we get:

$$\int_{t_i}^{t_f} \epsilon_{\text{feed}} \epsilon_r \dot{M} c^2 dt = \frac{GM_r^2}{r_r}, \quad (3)$$

where ϵ_{feed} is the efficiency of feedback coupling, which we set to 0.05 as the value typically adopted by the community (e.g., Di Matteo et al. 2005), ϵ_r is the radiative efficiency, \dot{M} is the accretion rate, and r_r is the radius of the region. The amount of gas accreted by the black hole seeds is then given by:

$$\Delta M_{\text{BH, reservoir}} = \frac{1}{\epsilon_{\text{feed}} \epsilon_r c^2} \frac{GM_r^2}{r_r}. \quad (4)$$

We assume that $\Delta M_{\text{BH, reservoir}}$ is accreted at the Eddington rate of the black hole. However, given the uncertainties on the properties of the ambient medium, we do not try here to estimate the luminosity output of those events, and we postpone this further modeling to a future work.

The model developed here relies on few parameters, whose values are set by the hydro-simulation results of M10. The only parameter not well constrained by the simulations is r_r , the radius of the central reservoir. We decided to assume two values for this parameter, $r_r = 1 \text{ pc}$ and $r_r = 0.1 \text{ pc}$, which are plausible assumptions in the range of the characteristic sizes of the supermassive clouds found in M10. Given the importance of r_r in setting the final mass of massive seeds after their first accretion phase, most of the results in the next sections will be discussed for both values of this parameter.

After the formation and having accreted from the reservoir cloud, the massive black hole seeds can further grow when their host galaxy experiences a new merger. In those subsequent accretion events, the massive black hole seeds are treated in the same manner as the descendants of light seeds: they merge with the black hole hosted by the companion galaxy and grow according to equation 1. We use this prescription for black hole growth for all the mergers that do not satisfy the condition for the creation of a massive seed, as we do not have at the moment enough input from small-scale hydro-simulation to attempt a general new recipe that would hold for all kinds of mergers.

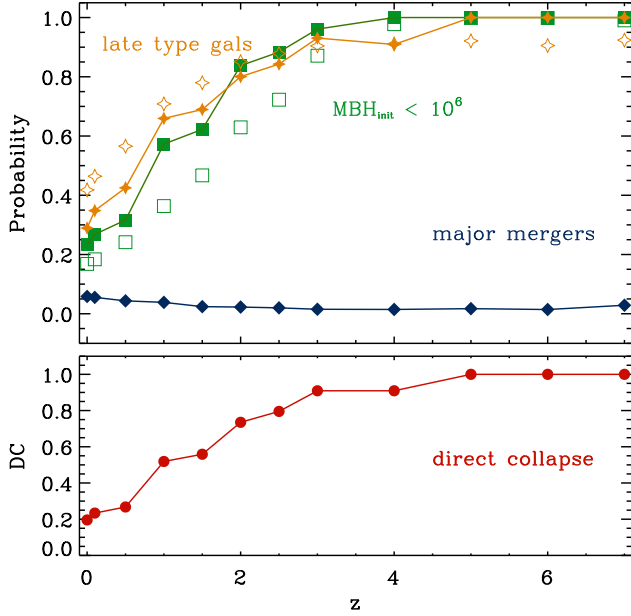


Figure 3. For the merger events of galaxies hosted by haloes of at least $10^{11} M_{\odot}$, probability of satisfying the conditions imposed for the formation of a massive seed via direct collapse: the blue diamonds show the fraction of major mergers, the green squares the fraction of merging galaxies with a black hole smaller than $10^5 M_{\odot}$, and the orange stars indicate the fraction of mergers that involve late-type galaxies. The red bullets in the lower panel indicate the fraction of major mergers that satisfy all the conditions for the formation of a black hole seed from direct collapse. The empty symbols indicate the fraction of galaxies with a small black hole and with late-type morphology for major mergers only.

Finally, if a massive seeds merges with a light seed, the new black hole will have the “light” or “massive” seed tag, depending on which black hole progenitor is larger.

3 RESULTS

After having set the theoretical assumptions that define our model, we now look at how frequently the imposed conditions for the formation of a massive seed are met as galaxies evolve from high redshift to the local universe (§3.1). We then look at the relative importance of black holes from massive and light seeds in defining the total black hole population (§3.2). Finally, we compare the typical environment in which the descendant of light and massive seed reside, trying to find differences which could help tracing back the origin of black holes (§3.3).

3.1 Statistics of events

We first of all explore if and how frequently the conditions for the formation of a massive seed from galaxy mergers described in section §2.3.2 are actually met in a realistic Λ CDM universe.

In the top panel of Figure 3, we show, as a function of redshift, the probability of satisfying each of our condition for the formation of a massive black hole seed. Of all mergers of galaxies whose remnants is hosted by a subhalo of at least $10^{11} M_{\odot}$, the fraction of major mergers (mass ratio 1 : 3, blue diamonds), is approximately

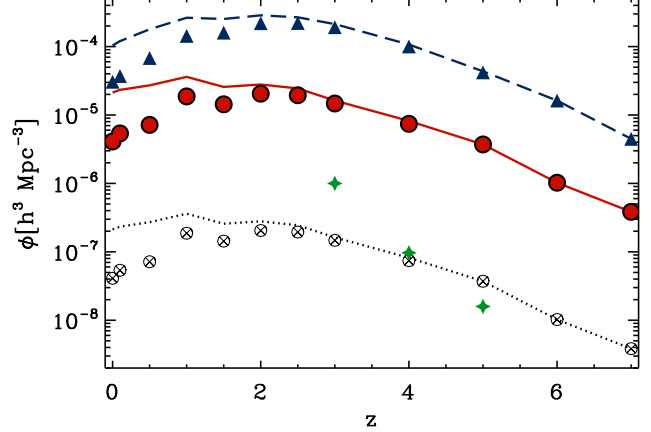


Figure 4. Number density of major mergers (mass ratio $> 1 : 3$) of galaxies hosted by subhaloes of at least $10^{11} M_{\odot}$, obtained from the rate of events and assuming a “visibility time” of 100 Myr (red solid line). Of these mergers, the number density of the ones that satisfy the requirements for the formation of a massive seed from direct collapse is indicated by the large red bullets. The blue dotted line and the blue triangles show the same quantities, but assuming that the threshold for major mergers is 1 : 10 instead of 1 : 3. Finally, the black dashed line and the crossed black circles show again the number densities of major mergers (with 1 : 3 mass ratio threshold) and events of massive seed formation, but assuming a “visibility time” of 1 Myr. The green stars indicate the number density of observed high-redshift quasars from Shen et al. (2007), put here to provide the reader with an order-of-magnitude comparison.

constant with redshift, and of the order of few percents. The fraction of merging galaxies hosting a black hole (descendant of a light seed) smaller than $10^6 M_{\odot}$ is, as expected, a strong function of redshift (green squares): at high redshift, the probability that a major merger involves galaxies with a small black hole is quite high (and even equal to one above $\sim z = 4$), but it decreases sharply at lower redshift and, in the local universe, about 20% of both merging galaxies have a black hole smaller than $10^6 M_{\odot}$. If the merging galaxies are experiencing their first merger, the mass of the black holes they host is still the mass assigned when the host galaxies were first formed. In this work, the mass assigned to these black holes, assumed to be the descendants of light seeds, is estimated using the outputs of the Millennium II simulation, as discussed in section §2.2. If we had assumed a fixed mass of $10^3 - 10^4 M_{\odot}$, as was done in previous works, the probability of satisfy the constrain on the pre-existent black hole mass would have been higher, in particular at low- z . Moreover, it might be plausible that the descendant of light seeds do not populate all galaxies, as we conservatively assume here, as some POP III stars might never reach high enough masses to form a black hole (see, eg., the discussion in Volonteri & Bellovary 2012). In this respect, then, the numbers shown here can then be considered as lower limits. On the other end, a channel of black hole feeding not considered in the reference model which could make black hole masses rise significantly before any merger takes place, is growth by secular instabilities. We tried to add this growth channel to look for any change in the statistics of events of massive seed formation found with our reference model. Our reference galaxy formation model already has a prescription⁴ for testing the instability of galactic disk: we sim-

⁴ The stability criterion used in the model is the one introduced by Mo et al.

ply assumed that when instability is detected, not only the bulge grows, but also a small fraction of the gas in the galaxy reaches the nuclear region and feeds the central black hole. While we find that the additional growth by disk instability has a detectable effect in increasing the total normalization of the black hole mass function, it does not influence the statistics of massive seed formation. Disk instability events, in fact, mainly take place in galaxies that never satisfy the other conditions for the formation of a massive seed: as discussed by Guo et al. (2012), disk instability is important for building up bulges in Milky Way-type galaxies, which we do not expect to be hosting a massive seed.

The other constraint we impose for the formation of a massive seed is the low bulge-to-disc ratio of the merging galaxies. The probability of having two disk galaxies involved in a merger is shown in the same figure (orange stars). The fraction of merging disk galaxies is also quite high (between 0.8 and 1) above $z = 3$, but decreases with decreasing redshift, as the total fraction of disk galaxies is lower. The morphology in the code is treated as in Croton et al. (2006) and De Lucia & Blaizot (2007); in a later development of the model introduced by Guo (2011), galaxies suffer a more gradual stripping of cold gas when they become satellites, with respect to the previous models. In this case satellite galaxies have even lower B/T ratio at all z , as the gas remains on the satellite and can keep cooling and forming stars in the disk, and central galaxies also have, on average, lower B/T disk ratio. With this newer version of the model, the fraction of merging galaxies with low B/T ratio would even be higher, and our estimates on the probability of satisfying the condition on the galaxy morphology can also be regarded as lower limits.

The resulting fraction of major mergers that satisfy all the conditions to form a massive seed black hole is shown in the lower panel of the same figure: all major mergers above $z \sim 4$ could potentially lead to the formation of a massive black hole from direct collapse. At $z \sim 2$ the fraction of major mergers that can form a massive seed has decreased to half, and in the local universe only 20% of major mergers lead to direct collapse. Yet, it is particularly interesting that our model predicts the presence of favourable conditions for the formation of black holes from direct collapse in a small fraction of major mergers in the local Universe. While we defer to future work a detailed study of the possible observational signatures of these events, in section §3.3 we briefly discuss some properties of their environment.

In Figure 4, we show the redshift evolution of the number density of major merger as well as of massive seed formation events. As from our simulation we have information on the *merger rate*, that is, the number of mergers per time interval within two subsequent snapshots, to obtain the number density of possibly visible events, we have to assume a typical timescale for the duration of the events. The numbers shown in the figure are obtained assuming, for each merger, a visibility time of 10^8 yr, which is approximately the estimated life-time of bright quasars (e.g., Martini 2004). Following this definition, the number density of major merger events of galaxies hosted by subhaloes above $10^{11} M_\odot$ is indicated by the red solid line. The red bullets show the number density of these major mergers that also satisfy all the condition for the formation of a massive seed: as discussed above, essentially all major mergers

at high redshift satisfy the conditions for the formation of a massive seed, while, at lower redshift, fewer major mergers can lead to a new massive seed. To guide the eye with an order-of-magnitude comparison, we plotted in the same figure the number density of high-redshift observed optical quasar reported by Shen et al. (2007). While a direct comparison between the observed quasar properties and our black hole population is beyond the scope of this paper, we see that the number of events possibly forming direct collapse seeds is large enough to account for bright optical quasars. In the same figure, the blue dashed line and the blue triangles show the number density of mergers and events of massive seed formation if the threshold for a major merger is decreased from 1 : 3 to 1 : 10, as used in Volonteri & Begelman (2010) in their study of the evolution of quasi-stars. Clearly, the number of events assuming a smaller mass-ratio threshold is much higher, approximately an order of magnitude higher at all redshifts. As discussed in section §2.3.2, we conservatively use a mass threshold of 1 : 3 in our reference model as mergers of galaxies with smaller mass ratios might not be violent enough to lead to the high gas inflow rates necessary to form a supermassive cloud. Finally, in Figure 4 we also show the number density of major merger and massive seed formation events for our reference model, but assuming a much shorter visibility time (1 Myr), which is approximately the life-time of the supermassive star and quasi-star phase. We postpone to a future work a detailed study of the observability of individual events of massive seed formation, but this would be approximately the number density of supermassive stars/ quasi-stars from galaxy mergers as predicted by our model.

3.2 Black hole properties

We now look at the global properties of the supermassive black holes descendant of massive seeds, comparing them both with observations and with the properties of black holes with a light seed progenitor.

We start by looking at the evolution of the mass function, for black holes both with light and massive seed progenitors (Figure 5). For the latter, we show the results obtained assuming both a 1 pc reservoir of gas and a 0.1 pc reservoir. In the first case (upper panel), the black holes from massive seeds (red curves) dominate almost the entire mass function at $z \sim 6$ and above; at $z = 4$ the mass function is already dominated by light seeds descendants (blue curves), except for the most massive end. For a smaller reservoir cloud (0.1 pc), the direct collapse black holes can grow to larger masses after their formation: in this case, a substantial number of black holes with masses above $10^8 M_\odot$ is already present at $z = 6$, and the direct collapse black holes dominate the massive end of the mass function to $z \sim 2$. In the local universe, in a wide mass-range, the number density of black holes from light seeds is a couple of order of magnitude higher than the number density of black holes formed from direct collapse. Only at the very massive end (above $10^9 M_\odot$), direct collapse black holes are about 10% of the total population for the 1 pc reservoir case. For the case in which the gas reservoir is 0.1 pc, at $z = 0$ and above $10^8 M_\odot$ the massive seeds descendants are only about one order of magnitude less numerous than the light seeds descendants with the same final mass. Around $10^{10} M_\odot$, the black hole with a massive progenitor are almost as numerous as the light seeds descendants. In the same figure, at $z = 0$, the grey band indicates observational estimates from Shankar et al. (2004), and, at $z = 2$ and $z = 4$ from Merloni & Heinz (2008). Finding the model parameters that better match the black hole mass function is beyond the goal of this pa-

(1998): the stellar disk of a galaxy becomes unstable when this inequality is met: $\frac{V_c}{(G_{\text{disk}}/r_{\text{disk}})^{1/2}} \leq 1$. If the disc is unstable (its mass in stars is larger than the mass that gives rise to the inequality), the excess stellar mass is transferred from the disk to the bulge to restore stability.

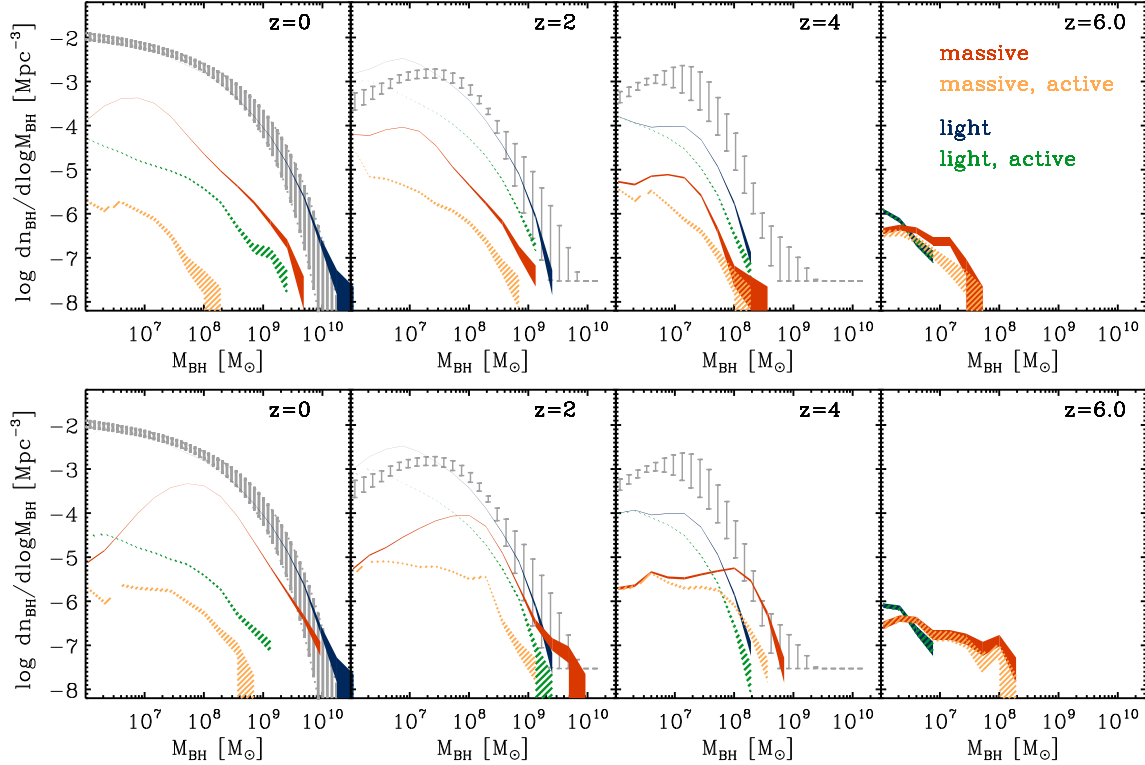


Figure 5. Black Hole mass function at various redshifts as indicated in the panels. For the top panels we have assumed that newly-formed massive seeds grow from a gas reservoir of 1 pc, while for the bottom panels a radius of 0.1 pc is assumed. The blue curve shows the mass function of black holes with a light progenitor, while the dark red curve shows the mass function of black holes with progenitor from direct collapse. The dashed curves indicate the mass functions of black holes emitting at more than 10% the Eddington limit, for the light seed descendants and massive seed back holes (light green and orange respectively). The width of the lines include the $1 - \sigma$ error. At $z = 0$, the grey band shows the black hole mass function calculated by Shankar et al. (2004), while at $z = 2$ and at $z = 4$ the grey band is the estimate for the mass function derived through a continuity equation by Merloni & Heinz (2008).

per, given also the still large uncertainties in the estimates of the mass function at high redshifts. We note, however, that the $z = 0$ mass function is very well matched by the current model, as also reported by Marulli et al. (2008). There is some discrepancy with the mass function estimated by Merloni & Heinz (2008) for $z = 4$, but we see that a smaller reservoir cloud could help increasing the mass function at the high-mass end, and possibly other channels of black hole growth, such as secular instabilities, could help increasing the normalization of the predicted mass function. Willott et al. (2010) attempted to estimate the mass function of the black holes powering the very luminous quasars observed at $z \sim 6$. When we compare with their results, we find a rough agreement at scales below $10^8 M_\odot$. At higher masses, where their mass function is best constrained, we unfortunately do not have model predictions, as the volume of the Millennium Simulation is too small to sample the population of rare massive black holes at those redshifts.

Finally, Figure 5 also shows the evolution of the active black hole mass function, where we define a black hole as active if it is accreting at a rate higher than 10% of its Eddington rate. Essentially all black holes with a massive progenitor are actively growing at $z = 6$, but the fraction of active black holes strongly drops with decreasing redshift (orange, dashed curves). This indicates that the most massive black hole seeds formed and grew at early time. Indeed the most massive end of the direct collapse black hole mass function does not evolve much below $z = 3$. On the other end, the descendants of light seeds are strongly growing at intermediate and low redshifts, and, by $z = 0$, they completely dominate the mass

function also at the highest masses. This is likely due to the fact that the most massive galaxies (and dark matter haloes), mainly assembled at late times (De Lucia & Blaizot 2007; Angulo et al. 2012), when the probability of satisfying our constraints for the formation of a massive seed is lower. It is not obvious how the accretion rates of massive seeds accreting from the gas reservoir translate into luminosity, we thus do not attempt here to predict the quasar luminosity function from the active black hole mass function shown here.

Thanks to the cosmological framework in which we work, we can directly compare the merger history of black holes with light and massive seed progenitors. Figure 6 shows several properties of the merger history of black holes that are descendants of light seeds and direct collapse black holes that had a first accretion phase assuming a reservoir of 1 pc. All quantities analyzed are plotted as a function of the black hole mass at $z = 0$; as both the descendants of light seeds and massive seeds (with $r_r = 1$ pc) show a relatively tight relation with galaxy mass (in Figure 7 we show the relation with bulge mass), studying the history of black holes at fixed mass, implies fixing the mass of the host galaxy. The top panels indicate the average number of progenitors⁵ (or mergers) that contributed to build up the black holes of final mass indicated in the x-axis.

⁵ We note that the absolute number of progenitors per galaxy (or black hole) depends on the resolution of the simulation, but the relative differences in the merger history of light and massive seed progenitors is insensitive to the resolution limits.

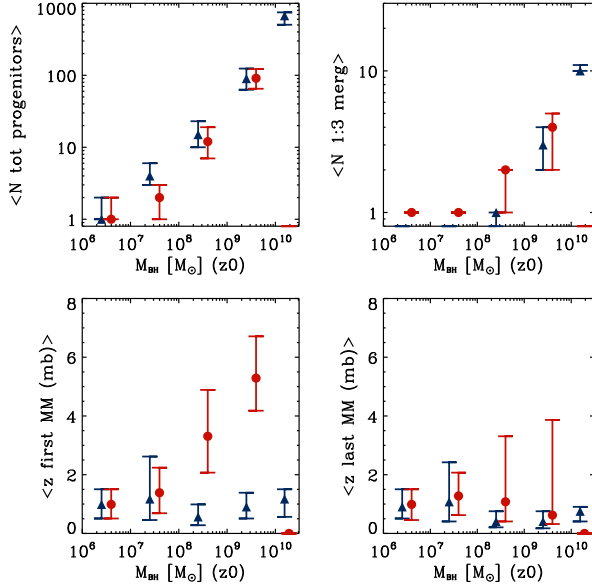


Figure 6. Merger histories of the galaxies hosting light seed descendants (blue triangles) and massive seed black holes in the model with a 1 pc reservoir (red circles), as a function of black hole mass at $z = 0$. The top left panel shows the average number of progenitors (mergers), while the average number of major mergers is shown in top right panel. The bottom panels show the average redshift of the first major merger (bottom-left) and the average redshift of the last major merger (bottom-right). The error bars bracket the 25th and the 75th percentile range.

Across all masses, light seed descendants and direct collapse black holes seem to have had a similar total number of progenitors (top-left panel). The most massive black holes are sitting in galaxies that had hundreds of progenitors. Of all the mergers, only few of them are classified as major (with mass ratio above 1 : 3). While there is a small evidence that the host galaxies of black holes from massive seeds experience more major mergers than the host galaxies of light seed descendants, the difference is not large, and the overall trend as a function of mass is the same for the two populations (top-right panel). The bottom panels show the average redshifts of the first and last major mergers. While there is only a mild difference in the typical redshift of the last major merger, with galaxies hosting light seeds having the last merger at lower redshift than galaxies hosting massive seeds (right bottom panel), there is a clear difference in the median redshift of the first major merger between the most massive light seed descendant and massive seeds descendant of the same mass (left bottom panel): black holes originated from direct collapse are sitting in galaxies that experienced a first major merger at much higher redshifts than the galaxies hosting light seeds and, as we have seen in Fig. 3, most major mergers at z above 4 potentially satisfy the conditions we imposed for the formation of a direct collapse black hole seed.

3.3 Black holes and their environment

Given that we are studying black hole seeds in a full galaxy-formation model applied to the outputs of the Millennium Simulation, we have the perfect framework to study not only the cosmological evolution of black holes, but also the large-scale environment in which black holes grow. Once black holes have experienced exponential growth to become the “mature” objects that

power AGN, it is impossible to recover information on the properties of their seeds, but the large scale environment might help us reconstruct the history of the hosted black hole.

3.3.1 Scaling relations

Figure 7 shows the relation between black hole and bulge mass at three different redshifts. The white-black area shows the position of the light seeds descendants on the $M_{\text{BH}} - M_{\text{Bulge}}$ plane, where darker pixels indicate a higher number density of objects. The success of the prescription of black hole growth described in Eq. 1 to reproduce the observed $M_{\text{BH}} - M_{\text{Bulge}}$, especially at high masses, has already been discussed in previous works (Croton et al. 2006; Marulli et al. 2008) (here the scatter is larger than previously shown as we include in the figure also satellite galaxies). For the growth of massive seeds soon after formation, we do not impose any preferred scaling with the mass of the host galaxy or dark matter halo, but rather a very simple self-regulation mechanism, where the main unconstrained parameter is the size of the reservoir cloud from which the new massive seeds can grow (see Eq. 4). In Figure 7 the red dots indicate where massive seeds descendants sit in the relation, for a 1 pc reservoir (upper panels), and 0.1 pc reservoir (lower panels), with the symbols color-coded depending on the redshift of formation of the seed. The oldest black holes from direct collapse formed around $z = 12$, and they are among the most massive black holes at $z = 0$, but there is also a large number of black holes that formed at later times and quickly accreted to the highest masses. In the 1 pc reservoir case, as soon as they are formed, the seeds sit on the relation, or slightly above it. It is interesting that the simple self-regulation mechanism for newly-formed massive seeds is able to bring them close to the relation, when $r_r = 1$ pc is assumed. During subsequent mergers, the black holes from massive seeds grow along the $M_{\text{BH}} - M_{\text{Bulge}}$ following the prescription for light seeds (Eq. 1), and, by $z = 0$, the most massive black holes show very little scatter. The picture is different when a 0.1 pc reservoir cloud is assumed: the seeds are allowed to grow to higher masses during the first phase of accretion, and only the black holes that experience many subsequent mergers head towards the relation. At $z = 0$, the most recently formed massive seeds are well above the relation. Assuming that the value of r_r would be in between the two values adopted here, our model predicts few outliers in the relation; detecting such outliers, however, might be observationally difficult, given the challenges in measuring directly black hole masses and given the low space-density of black holes descendant of massive seeds.

3.3.2 Properties of the host galaxies and haloes

In Figure 8 we show the morphological properties of the galaxies hosting descendants of light and massive seeds. The top panels show the distribution in bulge-to-total ratio of the galaxies hosting black holes with light seed (top-left) and massive seed (top-right) progenitor as a function of the black hole mass at $z = 0$. For the descendants of light seeds, small black holes live predominantly in disk-dominated galaxies (blue area), while the majority of massive black holes sit in bulge dominated galaxies (red area). For massive seed descendants, the morphology distribution of host galaxies is more constant across black hole mass, with an essentially negligible amount of black holes in purely disk galaxies. In the lower panels the same morphology distributions of host galaxies is shown for objects at $z = 2.5$ and, in this case, only galaxies hosting an

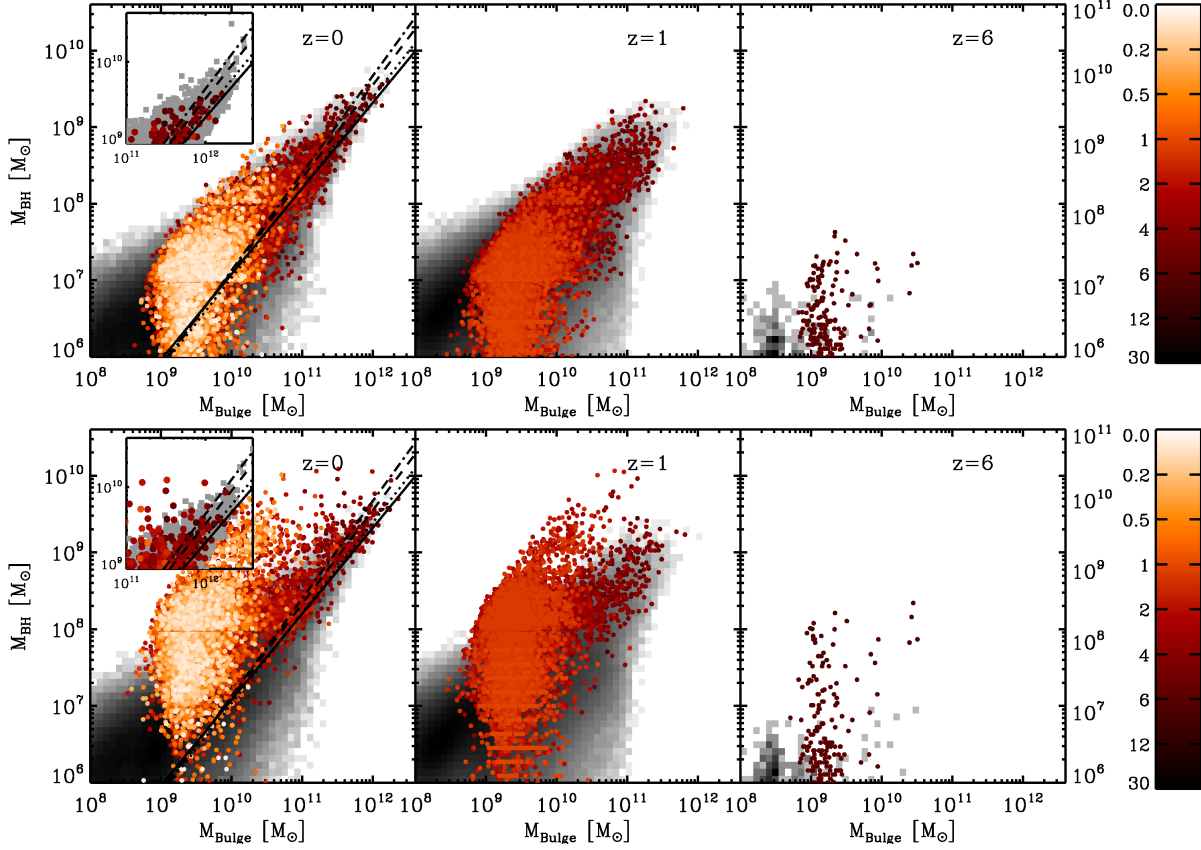


Figure 7. Relation between the black hole mass and the bulge mass at three different redshifts, as indicated on the panels. The grey area indicate the relation for light seeds descendants. The red points indicate the position on the relation for the black holes descendant of massive seeds. Darker red corresponds to higher formation redshift, as indicated in the side color bar. In the top panel the massive seeds formed assuming a radius of 1pc for the nuclear gas reservoir, whereas in the bottom panel the reservoir has been assumed to have a radius of 0.1pc. The solid lines at $z=0$ show some fit from observational data (Häring & Rix 2004; Gültekin 2009; Hu 2009).

active black hole (accreting at a rate higher than 10% of Eddington) are included in the calculation. At this redshift, very few black holes above $10^9 M_\odot$ are active (see the active mass function, shown by the dashed curves in Figure 5), so we exclude them from the present calculation. Black holes from light seeds sit mainly in disk-dominated galaxies, and only a negligible amount is in spheroids. The same holds for the active descendants of massive seeds in the $10^7 - 10^8 M_\odot$, but the smaller black holes (mainly recently-formed seeds) are essentially only hosted by ellipticals. Our model clearly predicts quite different morphological properties for the galaxies hosting light and massive seeds remnants, in particular for black holes of intermediate-small mass scales. Galaxy morphology could then contain important information on the origin of the hosted black holes.

We now look at the properties of the dark matter haloes hosting massive seeds. In the left panel of Figure 9 we show, at various redshifts, the mass function of the haloes (solid lines) and subhaloes (dotted lines) hosting newly-formed massive seeds (for central galaxies we take the virial mass of the halo as subhalo mass). The mass functions clearly peak at $10^{11} M_\odot$, as expected, given that we impose that value as the minimum halo mass where massive seeds can form. As in central galaxies, according to our definition, the subhalo and halo masses are equivalent, the two mass functions trace each other for massive seeds forming in central galaxies. This seems to generally be the case for massive seeds form-

ing in haloes smaller than $\sim 10^{12} M_\odot$. At larger masses, while the subhalo mass function drops quickly, the halo mass function flattens out and, at lower redshifts, reaches very high masses: these are massive seeds forming in subhaloes that are the hosts of satellites galaxies in larger haloes, that reach the masses typical of clusters. We find, in fact, that at $z=0$ about 20% of new-born massive seeds are in satellite galaxies.

In the right panel we show in which haloes the descendants of these massive seeds are today: seeds formed at very high redshifts sit in very massive haloes, with only a small fraction in haloes below $10^{12} M_\odot$. The descendants of seeds forming at more recent times are also sitting in massive clusters, but there is still a fraction of the population in smaller haloes.

3.3.3 Clustering

It is well known that the space distribution of dark matter haloes and galaxies can be different from the distribution of the underlying dark matter (Kaiser 1984; Bardeen et al. 1986). The two-point auto-correlation function⁶ provides information on how strongly a

⁶ The *two-point spatial autocorrelation function* $\xi(r)$ for a given class of objects is defined as the excess probability for finding a pair at a distance r , in the volume elements dV_1 and dV_2 : $dP = n^2 [1 + \xi(r)] dV_1 dV_2$, where n is

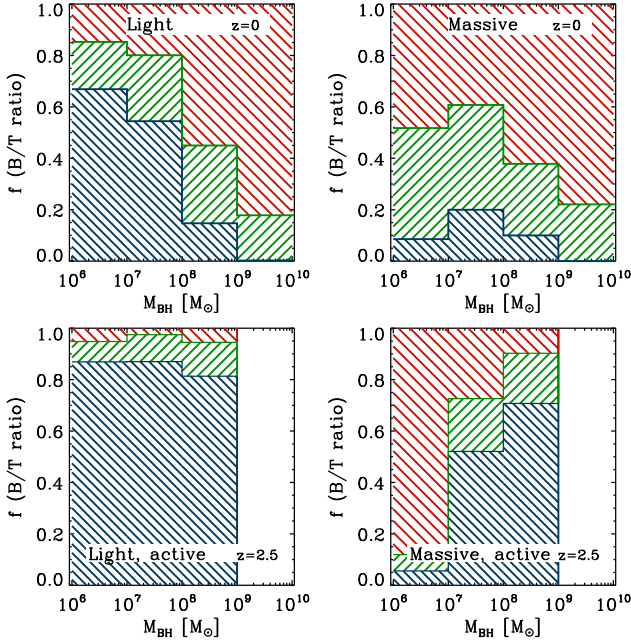


Figure 8. Morphological distribution of the galaxies hosting the descendants of light or massive seeds (left and right panels respectively), at $z = 0$ (upper panels) and at $z = 2.5$ (lower panels). At each black hole mass, the area of different colors indicate the relative contribution of galaxies with different morphologies, defined through the bulge-to-total ratio: blue refer to discs or extreme late-type ($B/T < 0.3$), green to normal spirals ($0.3 < B/T < 0.7$) and red to elliptical galaxies ($B/T > 0.7$). At $z = 2.5$, only active black holes are considered.

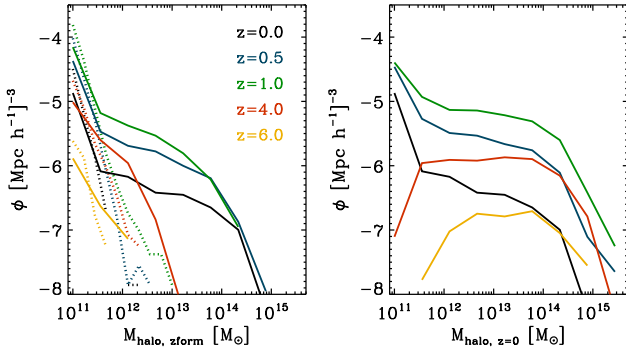


Figure 9. **Left panel:** At various redshifts, mass function of the dark matter subhalos (dotted lines) and haloes (solid lines) hosting newly-formed massive seeds. **Right panel:** local mass function of the haloes hosting the descendants of the massive seeds formed at the redshifts of the left panel.

given class of objects is clustered at a given scale, and from the amplitude and shape of this function is possible to extract important information on the environment of the objects analyzed.

One of the main advantages of studying galaxy evolution in models run on dark matter simulations rather than extended Press-Schechter models, is the possibility of studying the clustering of

a targeted set of objects, using the distribution of the dark matter haloes in which the objects reside.

At any given time, the most massive dark matter haloes are the most rare and biased⁷ objects, corresponding to the highest peak of the dark matter density field. While the clustering amplitude of dark matter haloes depends mainly on halo mass and only weakly on other properties, such as assembly history, concentration, recent mergers (e.g., Gao et al. 2005; Wechsler et al. 2006; Angulo et al. 2008; Bonoli et al. 2010), the clustering of galaxies depends strongly not only on mass, but also on galaxy properties such as color and surface density: for example, at fixed stellar mass, red and passive galaxies cluster more strongly than blue, star forming galaxies (e.g., Li et al. 2006), which is a consequence of galaxies of a given stellar mass, populating different dark matter haloes.

Here we want to study the clustering properties of galaxies that host the recent formation of a massive black hole seed, to further gain insights on the large-scale environment of these events. In Figure 10 we show the $z = 0$ two-point correlation function of galaxies that experienced a major merger that led to the formation of a massive seed (red solid curves). For comparison, we also show the two-point correlation function of all other major mergers at the same epoch that did not satisfy the conditions for direct collapse (blue dashed curves), randomly extracting, from the entire population, a subsample that matches the massive-seed population in number of objects and in the distribution of stellar mass (left panel), black hole mass (central panel) or halo mass (right panel). Using the same matching criteria, we also randomly extract subsamples from the entire galaxy population, and the correlation function of these objects is indicated by the green dotted-dashed lines. To calculate the uncertainty in the auto-correlations due to random sampling, for each matching criteria, we selected 100 random subsamples from the parent populations, and the error bars bracket the 10 and 90 percentiles of the distribution. We find that galaxies that recently experienced a direct collapse event are significantly less-clustered than the rest of the major-merger population and the entire galaxy population, when these are matched by stellar mass or black hole mass (left and central panels). Moreover, all recent mergers (both the ones that lead to a massive seed and the ones that preserve the small seed) are anti-biased with respect to the dark matter distribution. On the contrary, the random samples extracted from the entire galaxy population is slightly biased. Clearly, this indicates that galaxies with similar stellar mass or black hole mass cluster differently depending if they experienced a recent major merger. This is in line with the observational results indicating that blue-active galaxies are less clustered than red-passive ones. When matching samples by halo mass, these differences essentially vanish. We find, in fact, that, at fixed stellar mass, galaxies with a recently formed massive seed tend to be found in less massive haloes than the average galaxy and, when we match out samples by halo mass, the differences in clustering get erased as halo clustering depends primarily on mass. The smaller clustering amplitude of recent mergers (and, to an even larger extent, of mergers that lead to direct collapse), indicates that, in the local universe, anti-biased galaxies are the possible sites for finding on-going events of direct collapse. We find that these are mainly galaxies that lived in isolation for most of their lives, and that only recently experience encounters with other objects with similar properties.

We also looked at the clustering behavior of galaxies hosting

the average number density of the set of objects under consideration (e.g., Peebles 1980)

⁷ At any given scale, the bias parameter indicates how more (or less) clustered objects are with respect to the dark matter.

newly-formed massive seeds at high redshift, but we could not find a signal as strong as the one showed above: all samples show a similar clustering amplitude, independently on the assumed matching property. Unlike the $z = 0$ results, we also find that at high redshifts galaxies hosting a new massive seed show a much higher correlation function than the underlining dark matter distribution, which is expected, given that haloes above $10^{11} M_{\odot}$ (which is the imposed minimum mass in which massive seeds can form) reside in higher and higher density peaks as redshift increases. This is in line with quasar measurements at high redshifts ($z > 2$), which indicate that bright quasars are a highly-biased population, living in high density peak (e.g., Shen et al. 2007, 2009). In our model the black holes descendants of massive seeds dominate the massive-end of the mass-function at very high redshift (see Figure 5), so these could be the objects powering the brightest highly-clustered quasars.

4 SUMMARY AND CONCLUSIONS

In this paper we have introduced a new scenario for the formation of massive black hole seeds. Based on the results of the set of hydro-simulations from Mayer et al. (2010), we tightly link the formation of a massive black hole to the major mergers of gas-rich disk-dominated massive galaxies with no pre-existing massive black hole at their center. Such mergers can, in fact, easily channel a lot of gas at the center of the merger remnants, forming a sub-parsec scale cloud which will likely lead to a massive black hole seed either through direct gravitational collapse or, more likely, through a supermassive star/ quasi-star phase. In mergers of this kind, in fact, the accretion rate to the center are seen to be order of magnitudes higher than in isolated protogalaxies.

We developed a formalism to track such events in galaxy formation models to predict the evolution and environment of massive seeds across cosmic time. Rather than tuning the model free parameters that control the formation of massive seeds with observational data, we set their value using the findings of the hydro-simulations of M10, so that all our results on massive seeds can be considered genuine predictions of theoretical models. These are our main results:

- At redshifts above $z \sim 3-4$ almost all major mergers of galaxies residing in haloes of at least $10^{11} M_{\odot}$ meet the imposed conditions for the formation of a massive black hole seed. At lower redshifts the fraction of major mergers able to produce a massive seed strongly drops, and, by $z = 0$, the fraction has reduced to $\sim 20\%$. This dropping is due to the sharp decrease in the probability of having a major merger which involves two disk-galaxies with a still small black holes.
- Massive black hole seeds can dominate the massive end of the mass function above $z \sim 2$ or $z \sim 4$ depending on the radius of the gas reservoir from which they accrete just after their formation. Newly-formed massive seeds are, in fact, allowed to accrete from the surrounding gas until their feedback energy is able to unbind it. As the binding energy of the gas reservoir depends on its physical size (at fixed mass), massive seeds grow to larger masses in the model runs where the reservoirs are assumed to be smaller.
- Massive black hole seeds soon after formation sit on or above the $M_{\text{BH}} - M_{\text{Bulge}}$ relation, depending mainly on the size of the reservoir assumed. We generally expect a fraction of descendants of massive seeds to still be above the relation in the local Universe, but this population might not be easy to detect, given the predicted small number density of these objects and given the difficulties in measuring black hole masses directly.

- Massive seeds evolve very rapidly at high redshift, but do not grow significantly in the local universe. Of the most massive black holes today, the ones descending from a massive seed sit, in fact, in galaxies that had a first major merger very early. On the contrary, the massive descendant of light seeds are in galaxies that had a first major merger relatively recently, but grew very quickly to high masses.

- While the most massive black holes today sit in bulge-dominated galaxies, independently if they descend from a light or massive seed, the morphology of the host galaxies of smaller black holes is very different for the descendant of light and massive seeds: black holes between $10^6 M_{\odot}$ and $10^8 M_{\odot}$ with a light seed progenitor preferentially sit in disk-dominated galaxies while the descendants of massive seed in the same mass range are hosted by bulge-dominated galaxies.

- Galaxies that host massive seeds formed at very recent times have significantly lower clustering amplitude than a random subsample of the global galaxy population with the same stellar mass distribution. While this can be explained by the fact that, at fixed stellar mass, recent mergers take place in smaller haloes, the observational signature of this effect should be very clear.

Massive black hole seeds are a very attractive scenario alternative or, more likely, complementary, to models of light seeds from PopIII stars or the collapse of nuclear star clusters. While massive seeds from metal-free protogalaxies can only form at very high redshift, in this work we have shown that massive seeds from galaxy mergers, which do not require metal-free gas but rely on a different set of conditions, can form both at high redshift and at more recent times. While we have considered a purely hydrodynamical formation scenario for the massive seeds, which, at small scales, would be compatible with the quasi-star model of Begelman and collaborators, the results of our model should hold even if the ultimate collapse into a seed would take place in a different way, such as involving the core collapse of a massive nuclear cluster of normal stars (Davies et al. 2011), as long as the formation of the precursor supermassive gas cloud occurs under the conditions that we have considered here. Whether the “birth” of such black holes could be observed directly, is still very uncertain. A promising detection channel has recently been suggested by Czerny et al. (2012), who claim that quasi-stars might emit jets whose gamma-ray emission might account for the unidentified gamma-ray sources. The quasi-star phase, which has an emitted spectrum very similar to that of a red giant star, might be detectable with JWST at high redshift given the relative high frequency of seed formation events expected in models that rely on the merger rate of galaxies such as in our scenario or in other recent direct collapse models (Volonteri & Begelman 2010). On the other end, seed formation events happening at low redshift might be eventually identified by exploiting the information presented in this paper on the environment and nature of their host galaxies. Indeed, if they take place they should occur in underdense regions, perhaps in voids or at least field-like environments, where gas-rich, massive disk dominated spirals are common (good examples of such galaxies are indeed those in the local 8 Mpc Volume (e.g., Kormendy et al. 2010). We will dedicate a follow-up paper to a detailed analysis of the possible detectability of individual events at both high and low redshift.

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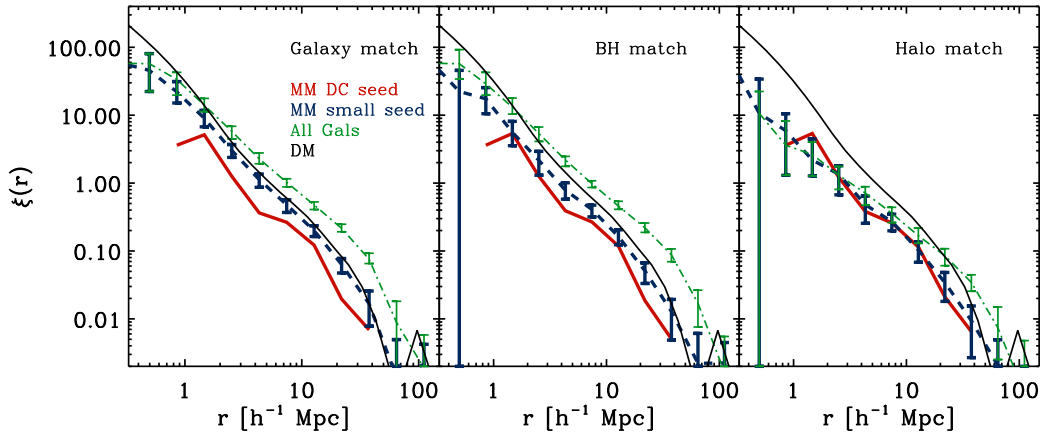


Figure 10. Two-point auto-correlation function of galaxies hosting the formation of massive black hole seeds from major mergers (red curves) at $z = 0$. The blue dashed curves and the green dotted-dashed curves show the correlation function of, respectively, other major mergers and the whole galaxy population with matching stellar mass (left panels), black hole mass (central panels) and dark halo mass (right panels). The solid line indicated the autocorrelation of the dark matter in the Millennium simulation.

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